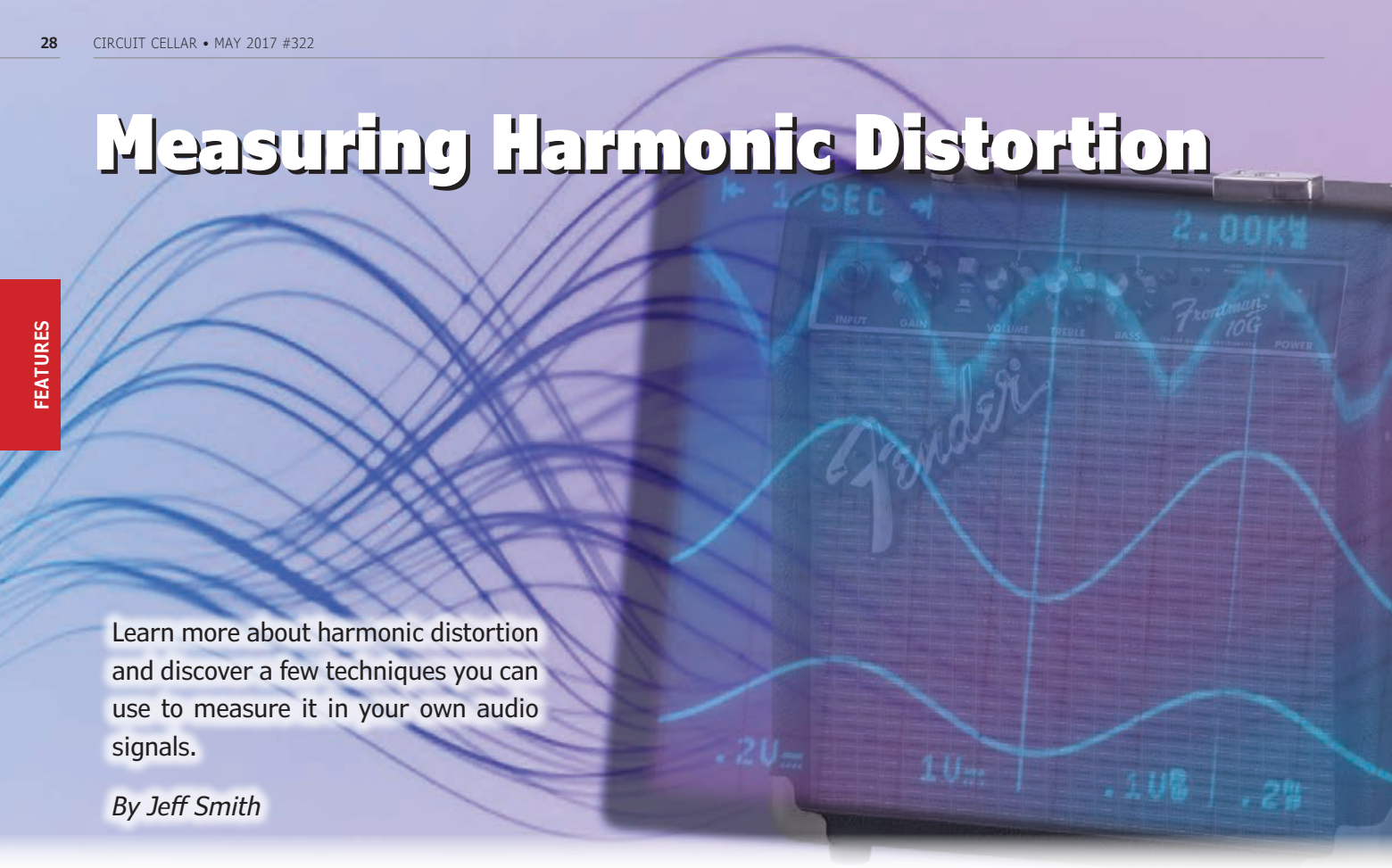
FEATURES

Measuring Harmonic Distortion



Learn more about harmonic distortion and discover a few techniques you can use to measure it in your own audio signals.

By Jeff Smith

Harmonic distortion consists of frequencies that are integer multiples of an input signal that appear as a result of signal processing. You may or may not want it along with your signal. Either way, it's educational to see and measure it. It helps you understand the relationship between audio as a signal and audio as a sublime rendering of your last electronic dance music (EDM) concert or dulcimer recital.

In this article, I will describe two methods of harmonic distortion measurement. To perform these measurements, you'll need a function generator or low distortion oscillator and an oscilloscope with at least two vertical input channels. You can build a simple circuit to measure signals with more than about 0.1% harmnic distortion. With a low distortion oscillator and a notch filter, you can measure down to about 0.003%. With the right oscillator, notch filter, and spectrum analyzer, you can accurately measure 1 ppm harmonic distortion.

Amplitude measurement in decibels expresses the way we hear loudness. It's not a linear function; it's logarithmic. Referenced to 1 VRMS = 0 dBVRMS, the relationships between dBV and RMS volts are:

20 × log (VRMS) = dBVRMS
10exp((dBVRMS)/20) = VRMS

A device whose output amplitude is larger than its input is said to have positive gain and is a positive number when expressed as a unit—or dimensionless (e.g., V_{PP}/V_{PP}) ratio in decibels. If the device's output amplitude is smaller than its input, it's said to have negative gain or attenuation and is a negative number in decibels.

Working with amplitude ratios in decibels is sometimes more convenient than in voltage or percent, once you get the hang of it. **Table 1**

VRMS	Ratio	dBVRMS	Percent
31.6 V	30:1	+30	3,160%
3.16 V	3:1	+10	316%
2 V	2:1	+6	200%
1 V	1:1	0	100%
707 mV	0.7:1	-3	70.7%
501 mV	1:2	-6	50.1%
316 mV	1:3	-10	31.6%
100 mV	1:10	-20	10%
10 mV	1:100	-40	1%
100 µV	1:10,000	-80	0.01%
1 µV	1:1,000,000	-120	0.0001%

Table 1
This chart describes the relationship between VRMS, ratios, decibels, and percent.

shows the relationship between VRMS, ratios, decibels, and percent. Although many of the relationships are not exact, they're almost always close enough to be useful and the inaccuracies are small. In most situations where you would multiply or divide in volts, you just add or subtract in decibels.

Decibels is the ratio of two amplitudes, without a reference point whereas dBVRMS is referenced to 1 VRMS. 1 VRMS = 0 dBVRMS. For example:

- For a power amp with +26 dB gain: +20 dB + 6 dB = (voltage gain of 10) × (voltage gain of 2) = voltage gain of 20

Referenced to 1 V (0 dBV):

- Harmonic distortion of 100 µVRMS = 100 µV/1 V = 0.01% HD = -80 dB
- Harmonic distortion of 50 µVRMS = 50 µV/1 V = 0.005% = 0.01% × 0.5 = −80dB − 6dB = −86 dB.
- Harmonic distortion of 400 µVRMS = 400 µV/1 V = 0.04% = 0.01% × 2 × 2 = −80 dB + 6 dB + 6 dB = −68 dB

Most harmonic distortion measurements here are just the ratio of harmonics to signal output level, hence just decibels.

DIFFERENCE CIRCUIT—CRUDE BUT SIMPLE

A simple way to see harmonic distortion on an oscilloscope uses a circuit that subtracts the original signal from your device under test (DUT) output and shows what's left, which are the frequencies and noise that were added. This is useful to get an idea of what the signals look like and for troubleshooting circuits that probably have 0.1% or higher harmonic distortion (e.g., tube power amplifiers). It can be used with music as well as static signals. Some power amplifiers use this idea to determine if the output is significantly different from the input. If a difference is detected, it might flash an LED to alert the user to overload conditions or suggest reduction in amplifier gain.

You'll need a common function generator with a sine wave output. The circuit uses components that will be tailored to your DUT and its environment. The components include op-amps, a power supply for them, a prototyping breadboard, resistors, maybe some capacitors, and an oscilloscope to observe and analyze the DUT input, output, and the difference between them. I'll contribute the circuit equations. Admittedly, using a function generator is not a precise way to measure harmonic distortion, but it'll give you a general idea of your gear's harmonic

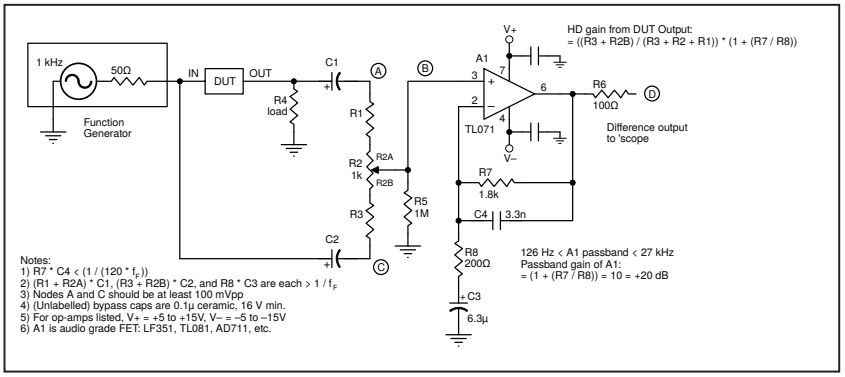


Figure 1
The difference for a device under test (DUT) whose output inverts the input signal.

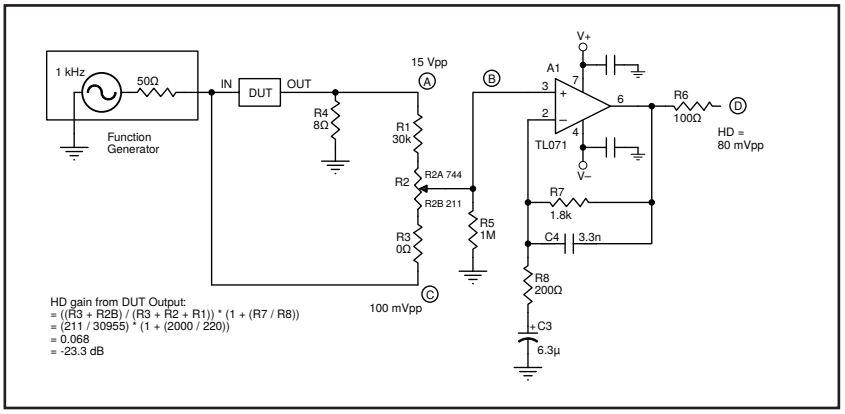


Figure 2
The schematic shows the difference circuit for tube guitar amplifier: an inverting amp.

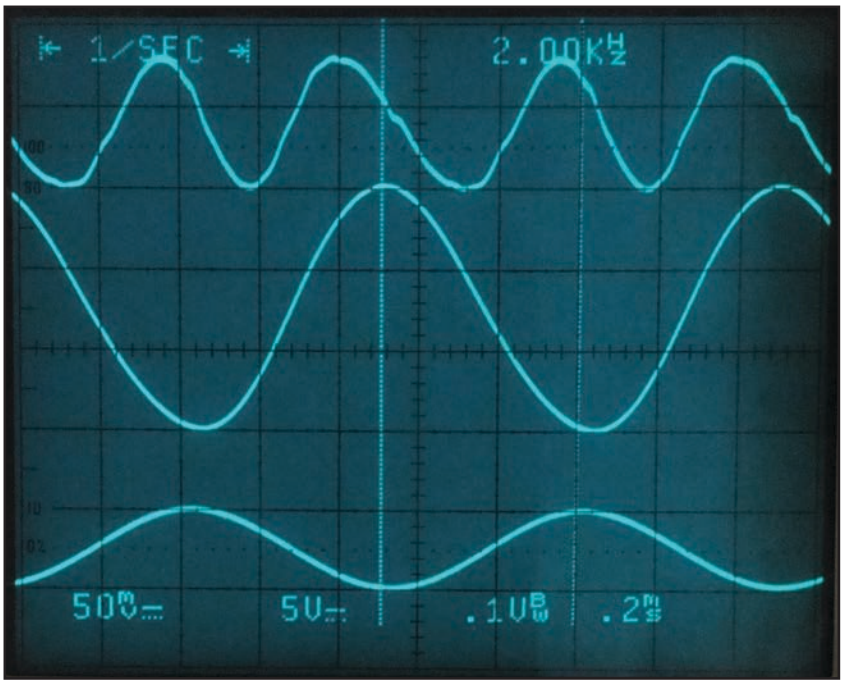


Figure 3
The oscilloscope photo shows the difference circuit waveforms for tube guitar amplifier. (Top: Node D. Middle: Node A. Bottom: Node C)

distortion performance. The circuit takes two forms: one for DUTs whose outputs invert the signal and one for DUTs that don't invert.

DIFFERENCE CIRCUIT FOR THE INVERTING DUT

Figure 1 shows the schematic of the difference circuit for inverting the DUT. Signal levels should be at least 100 mVpp. Don't forget the op-amp bypass capacitors. They keep your op-amps stable. Mount them close to the op-amp. You can omit or shunt C1 and C2 if the DC offsets of the generator and the DUT are less than 200 mV. Otherwise, leave them both in. Measure your offset for appropriate polarity.

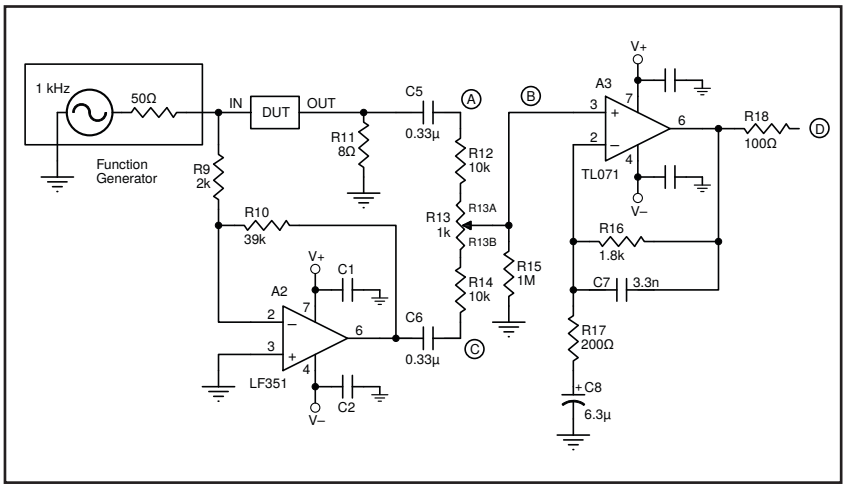


Figure 4
The schematic shows the difference circuit for a solid-state guitar amp: a noninverting amplifier.

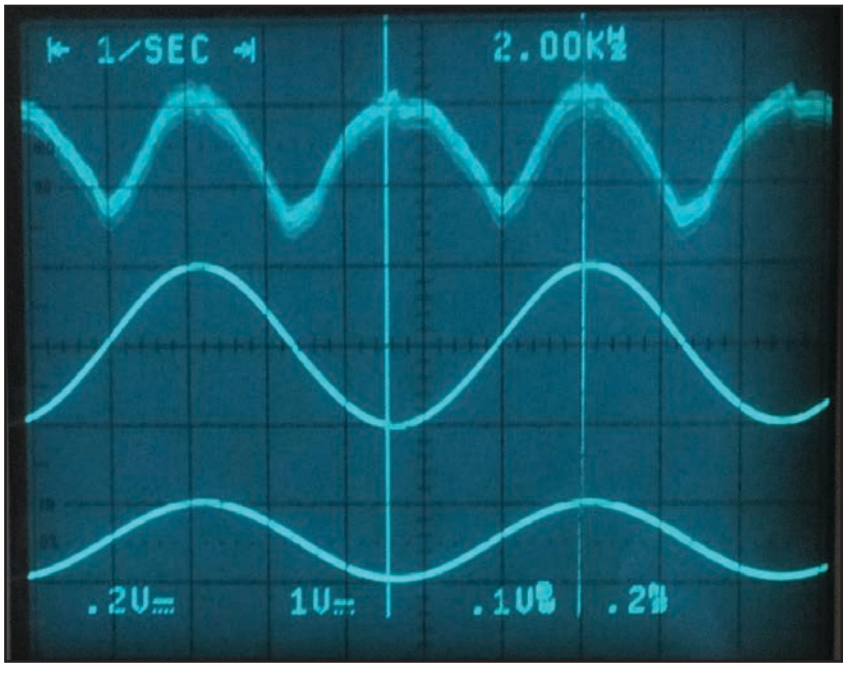


Figure 5
The oscilloscope photo shows the difference circuit waveforms for the solid-state guitar amplifier. (Top: Node D. Middle: Node A. Bottom: function generator output.)

The idea of R1, R2, and R3 is to balance the contributions of the function generator and the DUT output signals so that the fundamental cancels, and the DUT noise and distortion components are all that's left. R5 just sets the DC bias for A1. Observe point B on the oscilloscope before inserting A1 into the circuit. Adjust R2 for minimum signal amplitude. If the signal is less than 1 V_{PP}, put A1 into the circuit and monitor A1's output for better clarity.

R8 and C3 attenuate 60 Hz noise and DC offset. R7 and C4 attenuate high-frequency noise. These components depend on fundamental frequency (f_F). The values shown are for f_F = 1 kHz. Keep the time constants (R1 + R2A) × C1, (R3 + R2B) × C2, R8 × C3 each greater than $1/f_F$ and keep R7 × C4 less than $1/(120 \times f_F)$ to ensure you're not attenuating frequencies of interest.

Using an oscilloscope, monitor your DUT input and output with music playing to get an idea of the average signal levels. Leave the controls where they are to measure harmonic distortion at your normal listening level. Keep or substitute into the difference circuit whatever resistive load the DUT sees in your system (e.g., 4 to 8 Ω for a power amp, 10 to 100 kΩ for a preamp).

Determine the values for R1, R2, and R3 from the amplitudes at nodes A and C. Compute equal currents from the nodes to the trimpot wiper. Pick resistor values that will result in a current between 100 and 500 µA. For example:

$$\frac{A}{(R1+R2A)} = \frac{C}{(R3+R2B)} = 300\mu A$$

Observe resistor power ratings for high voltage outputs. Although the fundamental will ideally be nulled at the trimpot wiper, the attenuation of the harmonic distortion components is just a voltage divider from node A to Node C, with the wiper being the divider tap. Compute the gain from DUT output to A1's output as:

$$\left(\frac{(R3+R2B)}{(R3+R2+R1)}\right)\times\left(1+\left(\frac{R7}{R8}\right)\right)$$

If there's so much phase shift or time delay that you can't null out the fundamental, you'll need to either test at a different frequency, adjust the tone controls on your DUT, or use a different test method. Any noise at the DUT output that is not from the signal source will appear along with the harmonic distortion.

I used the circuit shown in **Figure 2** to measure the harmonic distortion of 1 kHz through a tube guitar amplifier.

For my tube guitar amplifier with a gain of 150: R1 = 30 kΩ, R3 = 0 Ω. R2's approximate wiper position is such that R2A = 744 and R2B = 211. Then:

$$\frac{A}{(R1+R2A)}=\frac{C}{(R3+R2B)}=\frac{15}{(30744)}=\frac{0.1}{(211)}$$

Figure 3 shows the waveforms of the tube guitar amplifier's difference circuit. A1's output is almost pure second harmonic distortion (2 kHz) at 80 mVpp. The gain from the DUT output to A1 output is 0.068. The harmonic distortion at the DUT output is: 0.08/0.068 = 1.17 V

The harmonic distortion referred to the DUT output is: 1.17 V/15 V = 7.8% (–22.1 dB). Rockin!

DIFFERENCE CIRCUIT FOR NONINVERTING DUT

Most of the previous suggestions apply here. Another op-amp is needed for this circuit to invert the generator output. The inverter gain can be set so that its output amplitude more closely matches that of the DUT as long as the inverter output doesn't add distortion to the signal by clipping, slew rate, or bandwidth constraints. Other than amplitude, the inverter output must be an accurate replica of its input. **Figure 4** shows the circuit used to measure a solid-state guitar amp.

Figure 5 shows waveforms of the solid-state guitar amp difference circuit.

LOW-DISTORTION OSCILLATOR

Most function generators have about 1% harmonic distortion, most of which is nulled out in the difference circuit. For harmonic distortion measurements below about 0.1% (–60 dB), you need a low-distortion oscillator. Linear Technology's datasheets describe several low-distortion oscillators designed by Jim Williams. We send this signal through the DUT and then, as before, arrange to . . . remove it. But if the harmonic

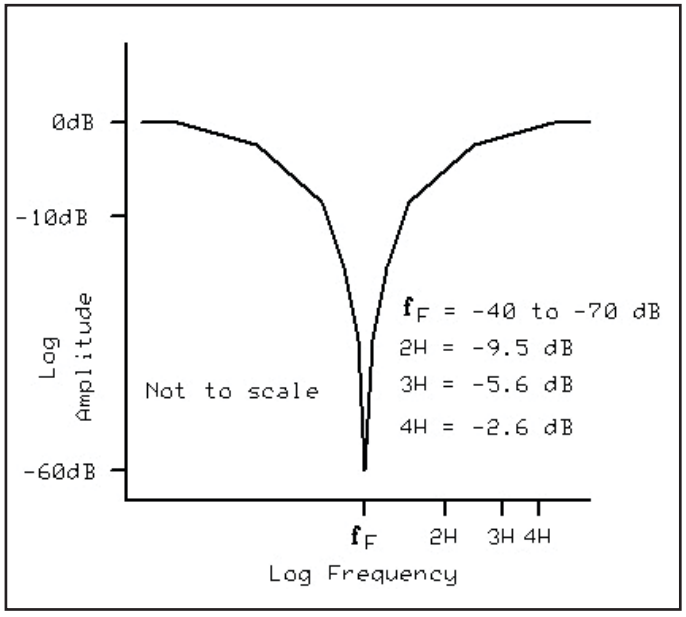


Figure 6
This is the notch filter frequency response. The fundamental frequency is greatly attenuated, the harmonic distortion frequencies not so much.

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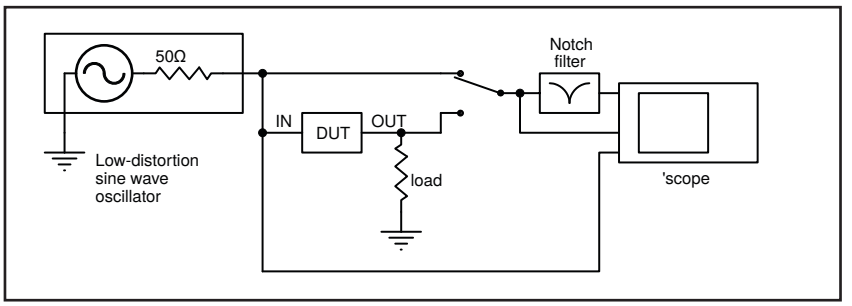

Figure 7
Here is the harmonic distortion test setup with the notch filter.

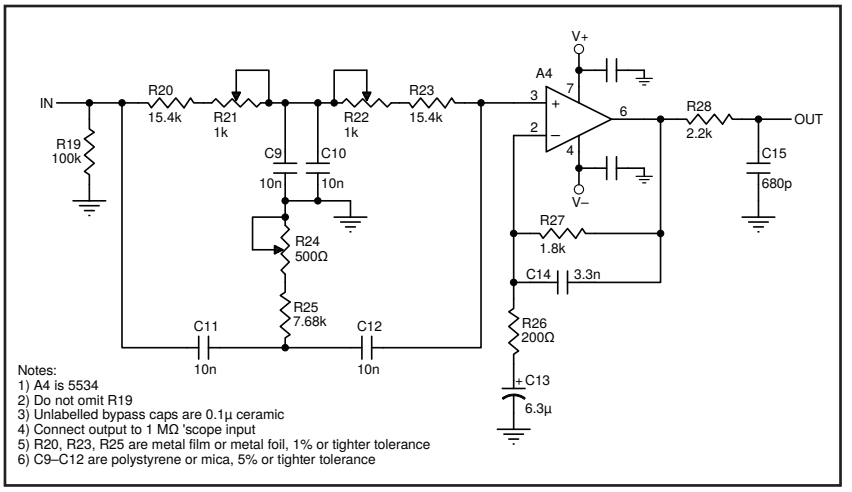

Figure 8
Use this schematic for the 1-kHz notch filter followed by +20 dB gain.

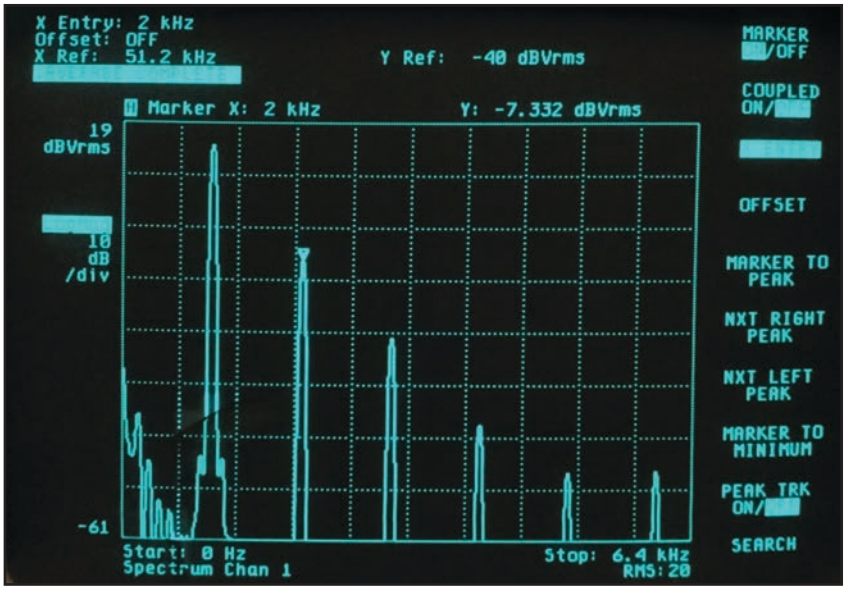

Figure 9
The spectrum analyzer display shows the tube guitar amp output with 1 kHz at +15.0 dBV and 2 kHz at –7.3 dBV.

ABOUT THE AUTHOR

Jeff Smith explores retirement by conceiving, designing, building, enjoying, abusing, and then ritualistically destroying his hi-fi, test, and music equipment.

distortion is so small that an oscilloscope can't display it, we need to add another tool.

NOTCH FILTER

A pure sine wave consists of a single frequency. A notch filter can attenuate that frequency by 60 dB or more without really affecting nearby frequencies. A filter designed and tuned for our purpose will attenuate second harmonic distortion by 9.5 dB (i.e., –9.5 dB), third harmonic distortion by 5.6 dB, and fourth harmonic distortion by 2.6 dB (see **Figure 6**).

The downside of this steep notch is that the frequency of maximum rejection will vary over time, due to the components' coefficient of temperature and temperature gradients between them. The same is true of an analog RC oscillator: the output frequency will drift for the same reasons. There are ways to minimize this problem. For example:

- Use components with low coefficient of temperature
- Minimize temperature gradients between components by waiting for warm-up, physical barrier, potting, Styrofoam, wadded newspaper
- Add a circuit that locks onto the fundamental frequency

Remember that for our purpose, a notch filter removes just one frequency—the fundamental. You'll be left with not only harmonics but also circuit noise, AC line noise, and anything else that's within the passband of the filter. This can be a problem if you need to see harmonics below about -100 dB in the time domain, but it can also be a good thing. It can help analyze ground loops or tell you if your dynamic-dependent signal processor operates differently with and without a signal.

Figure 7 shows the setup with the filter. With the right components, a suitable notch filter is not hard to build. **Figure 8** shows a passive notch filter followed by +20 dB gain and additional filtering. Connect the output to 1 MΩ oscilloscope input.

Xicon 23PS310 10 nF 5% polystyrene capacitors look suitable for C9–C12 (see Sources). This design will notch a range of frequencies around 1 kHz. The component values are ideal. If your low distortion oscillator frequency doesn't drift much, you can alter the fixed resistor values so that you can use potentiometers of smaller value, which makes tuning much easier—10-turn wirewound potentiometers are great for this. Watch the fundamental recede into the noise floor on the oscilloscope as you slowly tweak the potentiometers. Feel the analog love.

As with the difference circuit, if your

output signal is larger than 10 V_{PP}, make sure the notch is tuned reasonably close to the fundamental by adjusting it first with the switch in the position shown so you don't damage the filter's op-amp.

The notch filter results are less clear with extremely linear amplifiers. With the gain of 10 (A4), the typical oscilloscope waveform of the filtered output will look fuzzy with noise. More gain just gives you a bigger fuzzy waveform. And the waveform may look choppy or stupidly lumpy if it's a combination of two or more frequency components. You can design low-pass and high-pass filters for noise as long as they don't attenuate the frequencies of interest, and bandpass filters to zero in on individual harmonics. It can be done, but shouldn't you get out more?

If you're this far into it and you're willing explore software, go for the hot setup. The best way to see all the details (except phase) on one display with precision and a low noise floor is to add a spectrum analyzer to our test system to monitor the notch filter output.

SPECTRUM ANALYZER

Because of AC line noise and high gain amplifier noise, it gets difficult to see or measure harmonic distortion below about 1 mV on an oscilloscope without additional gain and filtering. And if you're looking at the waveform, it takes some practice to determine the amount each harmonic contributes if no single harmonic dominates the signal.

A spectrum analyzer displays amplitude on the vertical axis and frequency on the horizontal axis. Noise floor displays as a rough horizontal line and each frequency component is like a pole sticking out of the ground. Each harmonic is easily located and measured via text, indicating the cursor's position as long as they're high enough above the noise floor (at least 6 dB) to ensure the amplitude is unaffected by noise. You can use it in place of or in addition to your oscilloscope.

Figure 9 shows the spectrum analyzer display of the tube guitar amplifier's output. **Figure 10** shows the spectrum analyzer display of the solid-state guitar amplifier's output. Do the analyzer results corroborate the difference circuit results? One way to check is to refer to the chart shown in **Table 1**.

Even an old, used but working hardware audio Fast Fourier Transform (FFT) analyzer such as mine (the HP35660A) costs as much as a decent power amplifier. But, there are many software spectrum analyzers available. If you try one, I recommend that you compare and corroborate the difference circuit output waveform with the analyzer result. I tried a few in the past but did not verify their accuracy.

Figure 10
This is the spectrum analyzer display of solid-state guitar amp output.

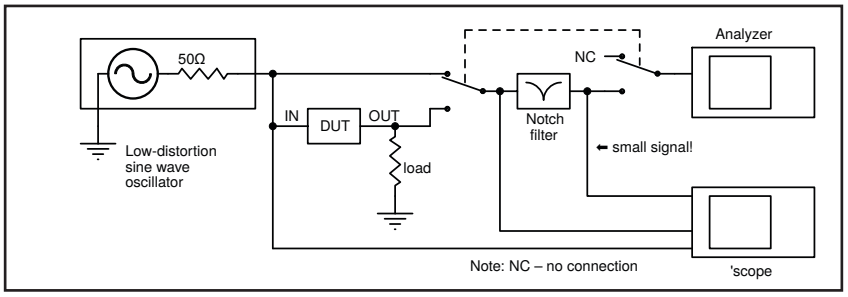

Figure 11
The hot setup consists of a low harmonic distortion oscillator, a notch filter, an oscilloscope, and a spectrum analyzer.

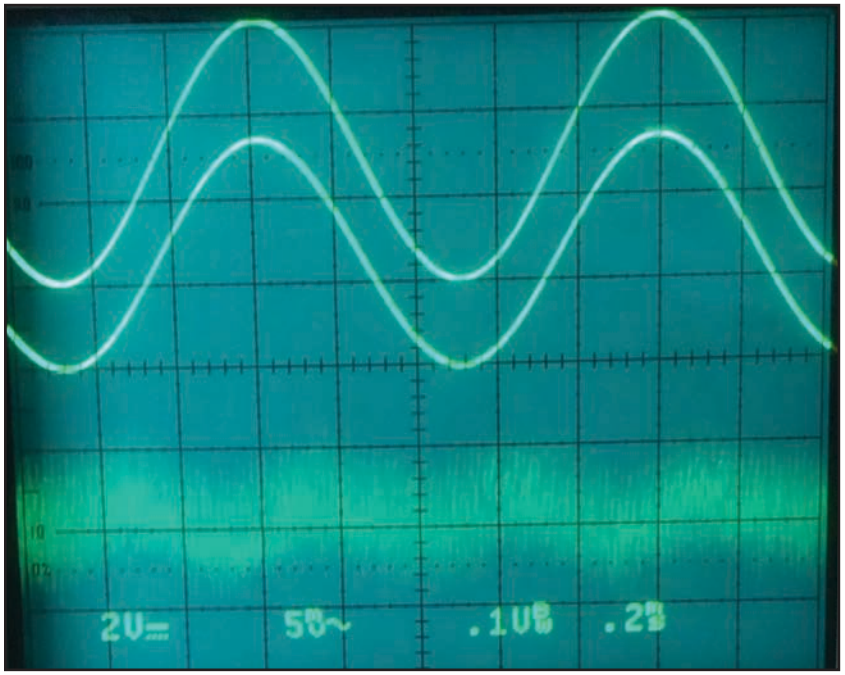

Figure 12
The oscilloscope display shows a solid-state hi-fi amplifier. (Top: Solid-state hi-fi amplifier output, 60 V_{PP}, 10× probe. Middle: Low harmonic distortion oscillator output, 2.7 V_{PP}, 10× probe. Bottom: Notch filter output: 2 mV_{PP}.)

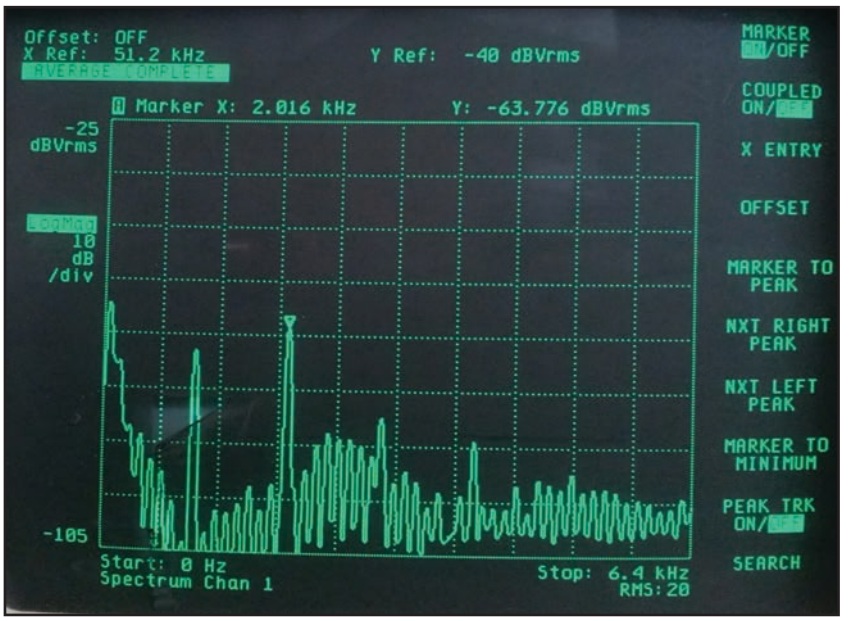

Figure 13
The spectrum analyzer display shows the hi-fi ampifier output with the fundamental notched out.

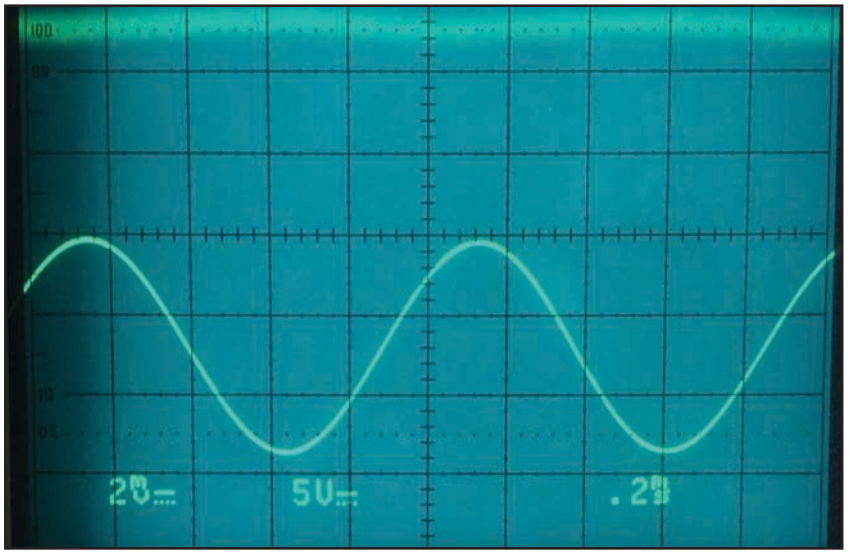

Figure 14
The oscilloscope display shows a low distortion oscillator. Top: Notch filter output, ~200 μV_{PP}. Bottom: Low harmonic distortion oscillator output, 13 V_{PP}.

There's a caveat for measuring harmonic distortion using just an analyzer. Even the best analyzers generate their own harmonic distortion, typically –80 dB below the fundamental. So if you're troubleshooting harmonic distortion below about –70 dB, the analyzer distortion will mask your DUT measurement.

The dynamic range—the range between the DUT output level and about 3 dB above the noise floor of the oscillator/analyzer—is greatly increased by attenuating the fundamental with the notch filter, then sending this signal to the analyzer input. If the filter attenuates the amplitude of the fundamental by 60 dB, the analyzer's dynamic range is increased by 60 dB. If the analyzer alone has an 80 dB dynamic range, the notch filter and analyzer test system together have a 140 dB dynamic range—a huge improvement. Problem solved: caveat empty (see **Figure 11**).

Always monitor the notch filter output on an oscilloscope before connecting to the analyzer. Make sure you understand and set your analyzer input sensitivity. Perform the switch function shown in **Figure 11** with cables and reduce the amplitude of the fundamental by tuning the notch before connecting the cables in the other switch position. Both software and hardware analyzers use analog components to see your real-world signal so make sure you don't overload the analyzer input. You don't want to replace your PC sound card or radio frequency front end. Oscilloscopes are more forgiving.

Figure 12 shows the oscilloscope display of the hot setup measuring a 275 WPC solid state hi-fi amp output with an 8-Ω load. The notch filter output is mostly second harmonic distortion, but how much? It can't be accurately measured without the analyzer.

Figure 13 shows the analyzer display of the solid state hi-fi amp output with fundamental notched out. The marker displays second harmonic distortion, clearly above the noise, at –63.8 dBVRMS.

MORE OSCILLATOR

What is the setup shown in **Figure 11** capable of measuring? **Figure 14** shows the oscilloscope display of an extremely low distortion oscillator output into the notch filter and the filter output. Where's the harmonic distortion? How much better can we measure with the analyzer (see **Figure 15**)?

The analyzer shows the notched fundamental and harmonics plainly above the noise floor:

- 1 kHz = –70 dBVRMS (notched), 2 kHz = –99.4 dBVRMS, 3 kHz = –103 dBVRMS—with 13 V_{PP} (+13.2 dBVRMS) sine wave output

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RESOURCES

"Plastic Film Capacitor Data," Larry Davis, 1998, www.interfacebus.com/Capacitance_Temperature_Change.html.

Resistor Materials, Resistor Guide, www.resistorguide.com/materials.

"Ultralow Noise Precision High Speed Op-Amps," LT1028 datasheet, Linear Technology, http://cds.linear.com/docs/en/datasheet/1028fd.pdf.

SOURCE

Xicon 23PS310 polystyrene capacitor
Mouser | www.mouser.com

- 2 kHz = –13.2 – 99.4 – 20 + 9.5 = –123 dB
- 3 kHz = –13.2 – 103 – 20 + 5.6 = –130 dB

The hot setup is a test system that can accurately measure individual harmonics below –120 dB (1 ppm). You can get an idea how steep the notch is on a spectrum display by tuning the filter while watching the frequency components. The fundamental's amplitude will bob up and down as you search for the deepest notch, but the amplitudes of the harmonic levels barely change at all.

IN SUMMARY

You can use a function generator and the circuits shown to accurately measure harmonic distortion from the painfully audible to 0.1% without big investment in time or money. With a better oscillator and a notch filter, you can measure somewhat lower. An excellent oscillator, a notch filter, and a spectrum analyzer enables you to measure to 1 ppm or less.

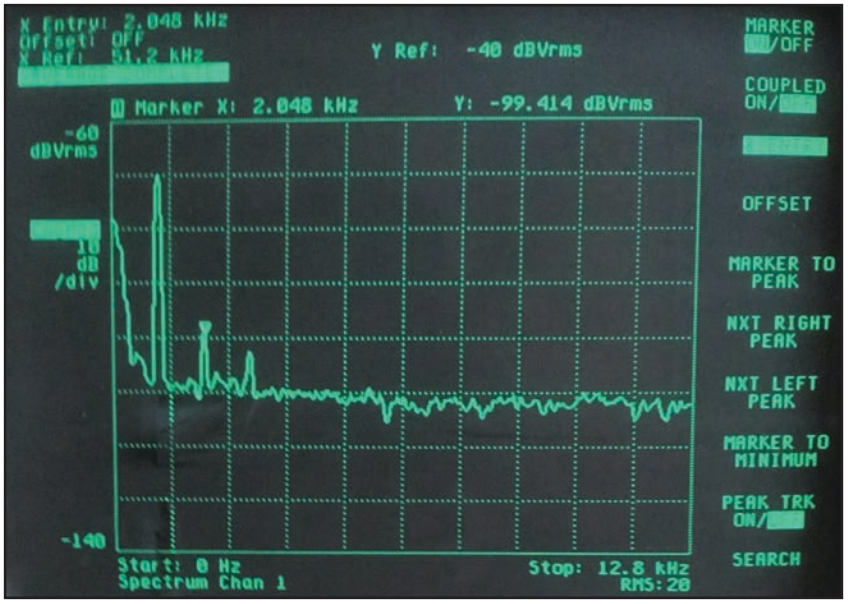

Figure 15
The analyzer display shows the notch filtered output of a low-distortion oscillator.

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